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Dynamics of Intertidal Gravel Dunes

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ABSTRACT

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The paper examines the dynamics of intertidal gravel dunes located at Hills Flat in the Severn Estuary, UK. Here a veneer of shale gravel (D_{50} = 4 mm) is locally deformed by strong tidal currents to form a series of flow transverse dunes with average heights and wavelengths of 0.6 m and 7.0 m, respectively. Incipient threshold values were much higher than expected owing to a coarse armor layer with D_{50} = 9 mm on the surface of the dune. More than 80 % of dune migration occurred during the first three days of the spring flows tide. During mobilisation and translation of the dune fine suspended sediment were released and concentrations were approximately one order of magnitude greater than the background level for this site. In a narrow range of hydraulic conditions highly localised and ephemeral secondary dunes were observed. Migration of the primary dune was accomplished without a measurable change in the dune volume supporting the view that the bedforms exist in quasi-equilibrium.

ADITIONAL INDEX WORDS: *Gravel dunes; armor layer; secondary dunes*

INTRODUCTION

In shallow coastal sea, estuarine and fluvial environments bed friction depends on not only the grain size of the bed material, but also the form drag associated with the bedforms. The former can be treated statically, but the latter interacts with the flow dynamically and can vary through space and time. For example, bedforms can vary over temporal scales ranging between seconds (wave periods) to weeks (spring-neap tidal cycles) and over spatial scales from a few meters to several hundred meters. Most existing understanding of bedform drag and sediment transport has been derived mainly from sparse field data and laboratory experiments with single bedforms. The response of multiple bedforms to changing hydrodynamic conditions, and the impact of these changes on sediment transport in the field situation remain poorly understood and imprecise. This has direct consequences for a range of engineering works where for reasons of safety over-design is necessary with consequent implications for project costs.

Although recent studies using computer models to investigate the detailed hydrodynamics and sediment transport over ripples have addressed some of these deficiencies (MACDONALD *et al*, 1999; LI *et al* 2006; PAN *et al*, 2006), present knowledge of bedforms, especially those composed of coarse material, is still very limited. In particular the areas of gravel dune formation and development, and dune interactions require more attention (SHERWOOD *et al*, 2000). The present paper follows work reported by WILLIAMS *et al*., (2006a, b) and focuses on some new aspects of intertidal gravel dunes dynamics. Observed changes in dune profiles are examined with reference to measured turbulent flow characteristics, bed shear stress and the hydraulic roughness of the bed. The net migration of a single primary gravel dune over a period of 10 days is described. The release of fine sediments when dune armor is disrupted is demonstrated and the evidence for the presence of ephemeral secondary dunes is presented. The study contributes to a broader understanding of little studied coarse grained bedforms.

METHODS

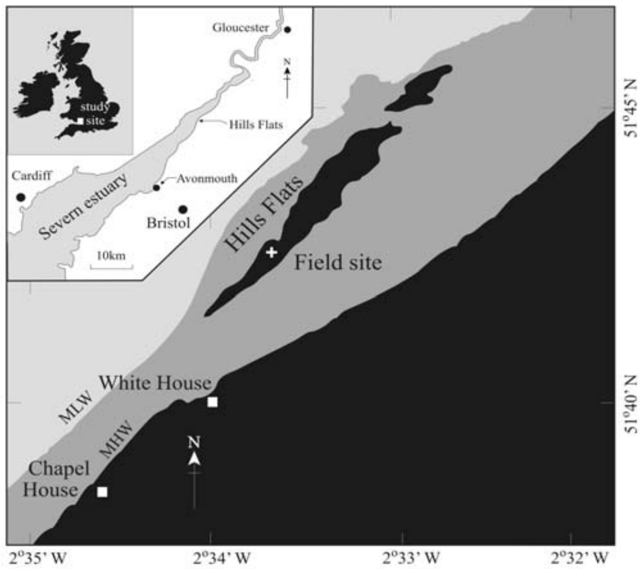

Figure 1. Location of the study site

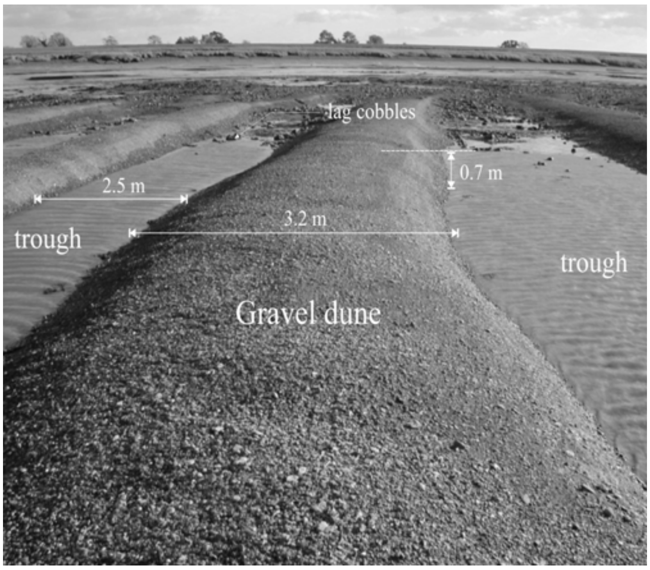

Figure 2. A typical PGD present at Hills Flat on Spring tides

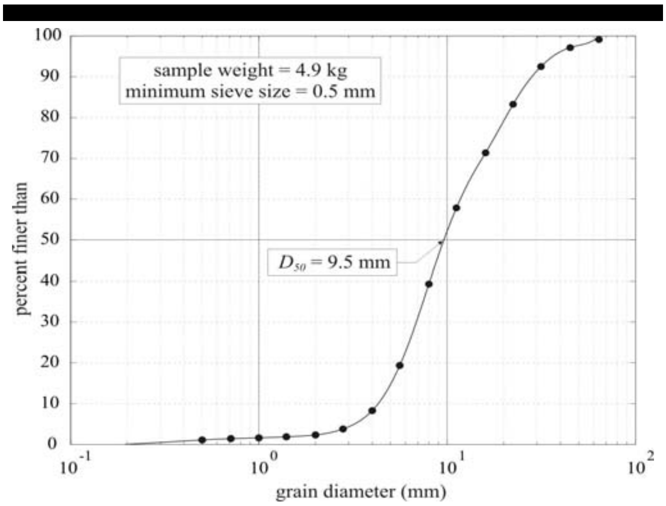

Figure 3. Grain size distribution of the PGD armor layer.

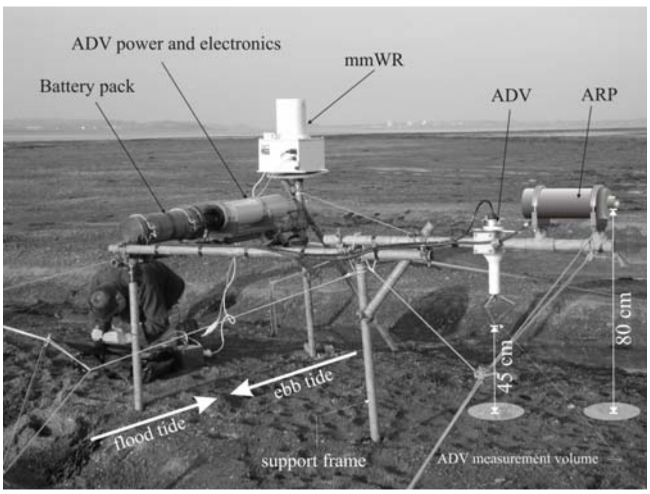

Figure 4. Instruments and deployment frame deployed above a mobile PGD in March 2003.

Field Site and Measurements

The primary gravel dunes (PGD) are located at Hills Flats in the Severn estuary, UK, (Figure 1). Here a thin veneer of platy shale gravel is found upon bedrock benches, (ALLEN and FULFORD, 1996). This is locally deformed by strong tidal currents c. 1 m/s to form a series of flow transverse PGDs (Figure 2) orientated approximately NW-SE with heights η, O(60 cm) and wavelengths λ, O(7 m), (ALLEN, 1993). During Spring tides, maximum current speeds reach around 1.37 m/s (Froude number 0.23) and the maximum dune inundation time is around 5 hours. The PGDs are essentially two-dimensional with straight to slightly sinuous crests.

The median grain diameter, D_{50}, of the PGD fraction coarser than 63 μm is 4 mm. Frequently, the larger fraction forms a distinctive armor layer (9.5 mm < D < 24.0 mm) on the upper stoss slope and crest region of the PGDs (Figure 3). Variable quantities of silt and clay are present in the void space of the gravel framework and sand is a minor component. The average bulk density of the dune sediment is 1316 kg/m^3. PGDs are observed to mobilise when the mean bed shear stress, τ, exceeds around 4 N/m^2. During peak Spring tides the profile of PGDs change in response to a reversal in tidal flow direction and on occasions a net downstream migration of the PGDs is observed over a period of approximately 10 days.

Surveys of the dune field were made using a total station. A rigid scaffold frame was used to deploy acoustic Doppler velocimeters, ADVs [see http://www.sontek.com], and acoustic bed profilers, ABPs [see http://www.marine-electronics.co.uk], (Figure 3). The instruments were positioned on the frame so that the ADV measurement points were located < 20 cm above the local surface of a migrating PGD. ABPs measured a 5 m length of the bed with a horizontal and vertical resolution of 0.01 m and 0.005 m, respectively (BELL and THORNE, 1997). ADV and ABP data were recorded at 25.0 Hz and 0.016 Hz, respectively, for 26 days from 3 March 2003 to 28 March 2003.

DATA ANALYSIS

Dune Profile Data

The transducer beam (width ≈ 1º) of the ABP scanned a 5 m length of the bed and measured the bed profile every minute. The present instrument was not designed for the turbid conditions in the estuary and multiple echoes were sometimes returned from the high-suspended sediment load. In pre-processing of the data set, each ABP scan was therefore screened and spikes were removed from the data set if the noise exceeded a pre-determined threshold.

A smoothing algorithm applied to the remaining ABP scans gave acceptably clear images by which to determine the location of the bed.

Hydrodynamics

ADV data were processed using SonTek ViewHydra Pro. V2.81 software to obtain values for water depth, h, and for the orthogonal turbulent flow components denoted U, V and W. This nomenclature refers to flow in the streamwise (approximately SW-NE), X, spanwise (approximately NE-SE), Y and vertical, Z, directions, respectively, and values of U > 0 and U < 0 denote ebb and flood tidal flows, respectively. Data were rotated to correct for vertical misalignment and de-trended to obtain zero-mean turbulent flow component time-series u, v and w. Instantaneous and time-averaged normal and shear stresses were computed using these time-series (WILLIAMS *et al*., 2006a).

When dunes are present, the total resistance to the flow comprises skin friction (or grain resistance) and the form drag attributable to energy losses as the flow separates downstream from the dune crest. However, since only the skin friction bed shear stress, τ'', is responsible for transport of the bed sediment as a bedload component of total sediment transport, it is critically important to obtain accurate estimates of τ'' when considering the dynamics of the present gravel dunes.

Here the approach by EINSTEIN (1950) is used where the thickness of the internal boundary layer (IBL), D' is related to the depth-mean current speed, S, the water surface slope I and the bed roughness by

$$\frac{S}{\sqrt{gD'I}} = 6 + 2.5\ln\left(\frac{D'}{k_N}\right) \quad (1)$$

where $I = \tau'/\rho gh$, τ' is the **total** bed shear stress, ρ is the fluid density, g is the acceleration due to gravity and K_N is the Nikuradse sand roughness parameter, (FREDSØE and DEIGAARD, 1992, p. 282) where

$$S = (\overline{U}^2 + \overline{V}^2)^{1/2} \quad (2)$$

and K_N = 2.5 D_{50} Estimates of the skin friction bed shear stress, τ'' can then be obtained using

$$\tau'' = \rho g D' I \quad (3)$$

(FREDSØE and DEIGAARD, 1992, p. 282). In the present study we following a more refined method based on the Einstein approach outlined by WHITE *et. al* (1980) to obtained estimates of τ''. Here it is noted that typically the local acceleration and the advection terms in the horizontal momentum balance at the present site are respectively < ca. 0.3 and 0.04 and thus the drag partitioning method outlined above should be applicable. In an attempt to adopt this approach in the present study, estimates of the measured time-averaged bed shear stress, τ, were obtained from the high frequency turbulence data using the well-known TKE and *Reynolds stress*, RS, or *eddy correlation* methods (e.g. SOULSBY and HUMPHERY, 1990). The bed roughness, expressed here as a drag coefficient at the ADV measurement height, was estimated using

$$Cd = \overline{\tau} \big/ \rho S^2 \,. \quad (4)$$

RESULTS AND DISCUSSION

The following section addresses some new finding derived from the Severn Estuary experiments 2003. A more comprehensive account of results is given by CARLING *et al*., (2006) and WILLIAMS *et al*., (2006a). The location of the deployment frame and instruments in relation to the PGDs is illustrated in Figure 5 using a rendered surface derived from the total station survey. This shows the extremely regular nature of the PGD field and is typical of bedform morphology during Spring tides. Although in places the PGD exhibit some 3 dimensional features, these were absent at the present study site. In the lower panel, measured transects along the PGDs are shown to illustrate the regular nature of dune spacing and heights and the slight asymmetries associated with some individual dune profiles. The solid block arrow is used to show the location of the deployment frame. Although dune asymmetry observed at low water is always determined by the direction of the ebb tidal flow, WILLIAMS *et al.* (2006a) report that PGD profiles also respond to flood tides. These cause a reversal in the ebb tide asymmetry.

The hydrodynamic conditions during a dune migration event are illustrated in Figure 6. The block arrow illustrates when dune

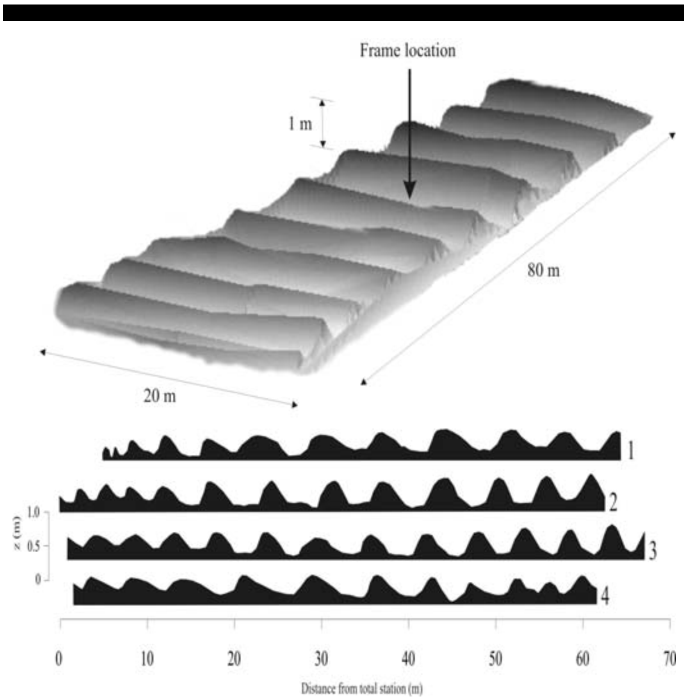

Figure 5. (*Upper*) PGD field site showing dune topography around the deployment frame (total station survey); (*lower*) survey lines. The upper profile is closest to the river and each line is approximately 50 m apart.

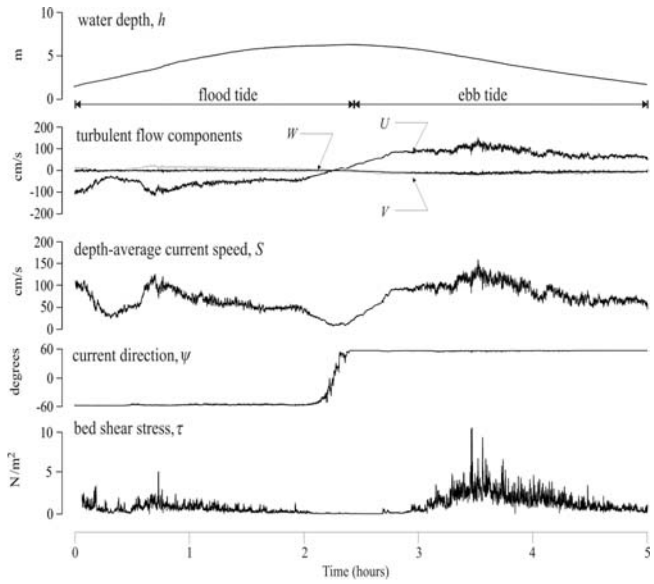

Figure 6. Time-series plots over a single tidal cycle showing water depth, turbulent flow components, depth-average current speed, current direction and total bed shear stress.

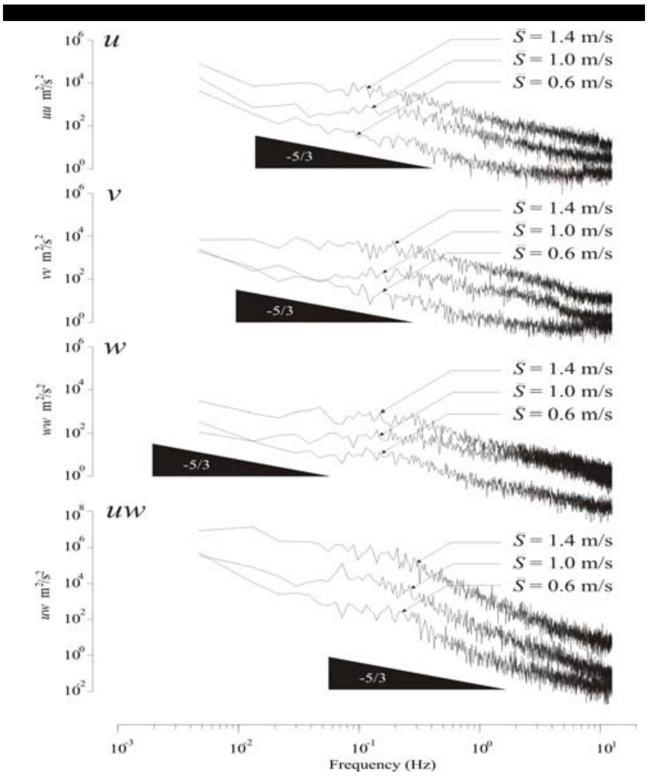

Figure 7. Typical *u*, *v* and *w* power spectra and *uw* co-spectra measured above the crest on a PGD at flow velocities of 0.6 m/s, 1.0 m/s and 1.4 m/s.

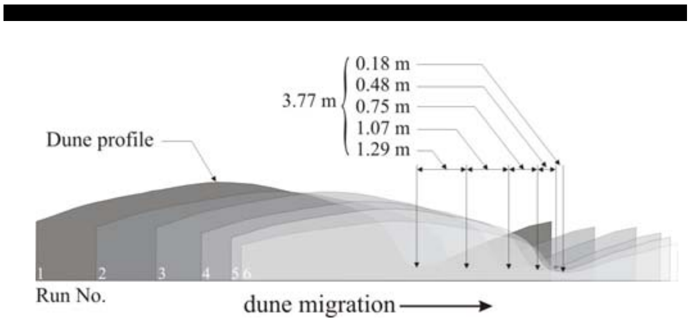

Figure 8. Migration of the PGD beneath the frame over a 10 day period: 1) start; 2) + 1 day; 3) + 2 days; 4) + 3 days; 5) + 5 days; 6) + 10 days.

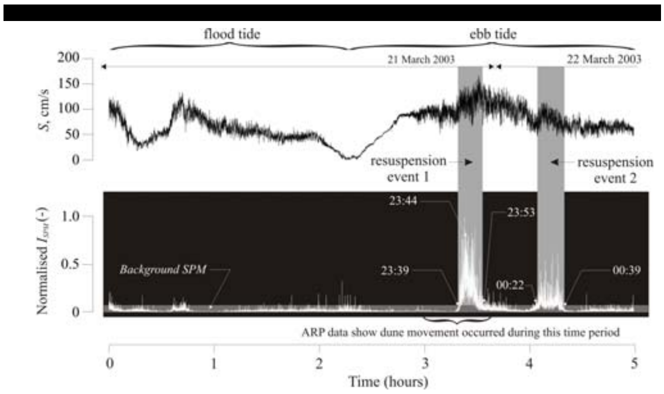

Figure 9. Plot showing the release of fine suspended sediments associated with the mobilization of the PGD during an ebb tidal flow.

motion was measured by the ARP and is coincident with the peak in bed shear stress.

Typical turbulence power spectra and co-spectra from the ADV are shown in Figure 7. The expected -5/3 spectral decay in the range $10^0 < f < 10^1$ is well demonstrated as is the increase in total energy associated with increases in mean flow velocity in the range 0.6 m/s < S < 1.4 m/s.

The net migration of the PGD beneath the deployment frame over a 10 day period is shown in Figure 8. Here the measured PGD profiles have been smoothed and anomalous data from the ARP resulting from multiple bed echoes have been removed. In total the PGD moves a distance of 3.77 m with more than 80 % of migration accomplished by the peak spring flows occurring during the first 3 days. Most sediment is lost from the crest and stoss regions. At greater temporal resolution it was observed that the PGD migrated in opposite directions dictated by the direction of the tidal flows (WILLIAMS *et al*., 2006a). However, owing to the tidal asymmetry at this site, the net down-estuary migration shown in Figure 8 resulted. Subsequent measurements above a PGD at approximately the same location in October 2005 showed that net dune migration was reduced to c. 2 m during slightly lower flow conditions.

Based upon measured bed shear stresses it was apparent that PGD migration only occurred when the bed shear stress exceeded the threshold of motion for the armor layer (WILLIAMS *et al*., 2006a) comprising sediment with D_{50} = 9 mm and thus exceeded significantly the theoretical threshold value for PGD movement. The rapid bedload transport associated with bedform mobilisation and translation also released a considerable quantity of finer sediments locked in the dune sediment matrix (Figure 9). Although during these resuspension events, bedload transport was intense and local SPM concentrations were c. one order of magnitude greater than the background level for this site, no measurable changes in the overall dune volume were detected. This indicates that bedform migration is essentially accomplished without a net loss or gain of sediment thus supporting the view that the PGD exist in quasi-equilibrium with the prevailing hydrodynamic conditions and the upstream sediment supply.

At low water, bedload sheets and other bedform-like features were sometimes preserved on the stoss slope and crest of PGDs (Figure 10). They were most common during flow conditions just below the threshold for mobilisation of the PGD armor. The ARP data showed that they were probably the washed out remnants of small dynamic ephemeral secondary dunes (SD) observed on occasions to migrate rapidly on the surface of the PGD during peak tidal flows (Figure 11, WILLIAMS *et al*., 2006b). The height and wavelength of the SDs were around 4 cm and 10 cm, respectively, and their occurrence and dynamic behavior appeared to be governed by the local hydraulic conditions. Data obtained thus far indicates that they flow reattachment in the trough regions of the PGD initiates their formation and that they play a role in sediment delivery to the crest region of the PGDs and thus to bedform migration. Predicted rates of bedload transport are found to compare well with the measured mass transport of sediment by secondary dune migration.

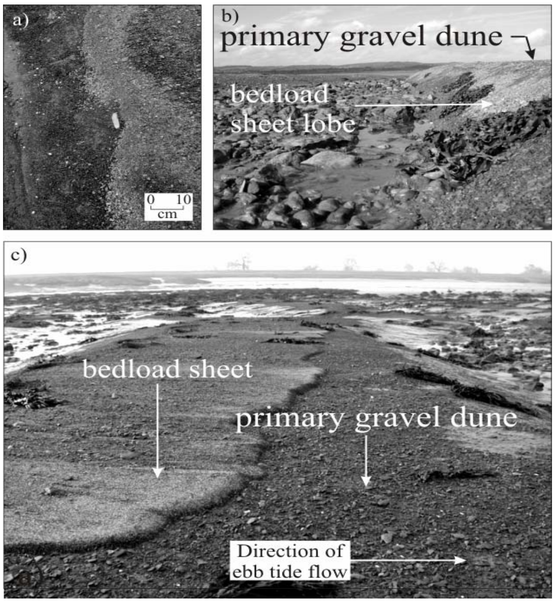

Figure 10. (a) Preserved secondary dunes (SD) on the stoss slope of the PGD; (b) a bedload sheet lobe deposited on the slip face of the PGD; and (c) a well-preserved bedload sheet along the crest of a PGD close to the present deployment frame.

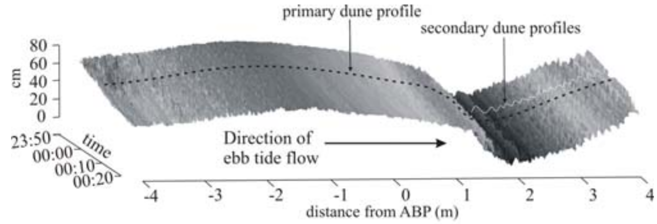

Figure 11. Plot showing the presence of ephemeral SDs along the stoss slope of a PGD.

CONCLUSION

The net downstream progradation of the dune during ebb tides is approximately balanced by migration in the opposite direction during flood tides thereby constrains the PGD to approximately the same location. Assuming sediment bypass volumes are low the results demonstrate that net sediment transport is low. However, more information is needed on the complex interactions between bedforms and rising/falling tidal flows. Incipient threshold values for the PGDs do not agree well with the observed dynamic behavior of dune owing to the armor layer. The sediment sorting processes responsible for development of armor layers require further study. The formation and subsequent migration of SDs appears to be restricted by a relatively narrow range of hydraulic conditions and requires the deposition of new sediments supplied when the profile of the upstream PGD adjusts to peak Spring tidal currents. They are highly localised and ephemeral in nature. The processes by which sediment is delivered to and distributed on the crest and slip face regions of the PGDs by the SDs and the processes by which SDs may evolve into BSs requires further study.

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